Final Project Report
Grant No. FA9550-05-1-0105

Mathematical and Computational Framework for Virtual Fabrication Environment for Aircraft Components

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Overview

The results of research performed under this project have been published, or are in the process of being published, in a dissertation and in refereed technical journals. Therefore, in accordance with instructions concerning the contents of final performance reports submitted to AFOSR, the objectives and main accomplishments of the project are summarized herein and references are given to the pertinent technical publications.

This project addressed fundamental questions that pertain to the utility of the methods of numerical mathematics in engineering decision-making processes. The basic methodology investigated under this project concerns the problem of selection, calibration and validation of mathematical models and thus transcends particular applications. Nevertheless, it is essential to have specific settings in which to illustrate the underlying concepts and procedures.

The problem of investigating the feasibility of a computational framework for virtual fabrication environment designed for cost-effective utilization of materials and manufacturing resources in the fabrication of complex aircraft and spacecraft components made of aluminum was chosen for this purpose for two reasons: First, this problem is of substantial importance to the Air Force. Second, validation of mathematical models requires correlation with carefully designed and controlled physical experiments. An unique opportunity existed for generating experimental data under tightly controlled conditions using state of the art equipment and techniques in the Metallic Processes and Prototyping Laboratory of Boeing Phantom Works in St. Louis.

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14. ABSTRACT

This project had a general and a specific objective. The general objective was to investigate the question of how mathematical problems should be formulated so that they can serve as reliable and accurate representations of physical reality in the sense that they will provide predictions of events or states of systems that can be confirmed consistently by physical observations. The construction of such mathematical models involves processes, the main elements of which are calibration, prediction, evaluation and modification. The specific objective was the development of the mathematical and computational aspects of a knowledge base needed for the creation of a virtual fabrication environment for aircraft components manufactured from 7050-T7451 aluminum plate stock so that the incidence of re-working and scrapping of partially or fully manufactured parts can be substantially reduced.

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Statement of objectives

The objectives were in two categories: General objectives and a specific, goal-oriented objective:

1. General objectives: One of the fundamental questions of numerical mathematics is how mathematical problems should be formulated so that they can serve as reliable and accurate representations of physical reality. In other words, a well-constructed mathematical model should provide predictions of events or states of systems that can be confirmed consistently by physical observations. The construction of such mathematical models involves a process, the main elements of which are calibration, prediction, evaluation and modification. The objective of this project was to develop and clarify guidelines for the selection of mathematical models based on correlation with experimental data and illustrate their applications.

2. The specific objective was to develop the mathematical and computational aspects of the knowledge base needed for the creation of a virtual fabrication environment for aircraft and spacecraft components manufactured from 7050-T7451 aluminum plate stock that will make it possible to plan the fabrication processes so that the incidence of re-working and scrapping of partially or fully manufactured parts is substantially reduced. This is expected to result in substantial affordability improvements for aircraft and spacecraft structures.

Air Force relevance

The relevance of the proposed project to the mission of the Air Force is described in this section with respect to the general and specific objectives of the proposed project.

General objectives

The Air Force spends very substantial amounts directly or indirectly for the acquisition of computed information in a variety of technological areas for use in engineering decision-making processes that include analysis, design and design certification. Airframe design and maintenance is just one of those areas of application.

The value of information acquired through applications of the techniques of numerical mathematics is strongly correlated with its quality. Reliable information will serve to reduce product cycle costs whereas engineering decisions based on unreliable data are very likely to cause problems. Unreliable data have negative economic value: Having misleading information is worse than knowing that some information is unavailable or substantial uncertainty (whether cognitive or aleatory) is associated with it. It is well known that finding problems late in the product cycle is generally very expensive in terms of costs and performance. The failure of the C-17 wing in a static test in October 1992 is a case in point [1].

This project addressed the general problem of quality assurance in model selection and the use of feedback information to guide the process of model selection. This problem was identified as a focal problem in [2]. The outcome was an improved understanding of the process of validation of mathematical models through correlation with experimental information. This very important aspect of numerical mathematics is receiving an increasing amount of attention in computational fluid dynamics (CFD) (see, for example, [3], [4], [5], [6]). Applications to problems in solid mechanics are of more recent origin.

Specific objectives

The increasing emphasis on affordability of military systems has led to a number of advances in airframe design and production. Unitized airframe structural components are replacing sheet metal built-up components to reduce part count and assembly cycle times and costs. The qualification of thick aluminum plate stock enables the machining of integral structure with a minimum of expensive tooling. The development of high speed machining (HSM) techniques has further enabled the fabrication of thin lightweight structures that provide improved performance at lower cost.

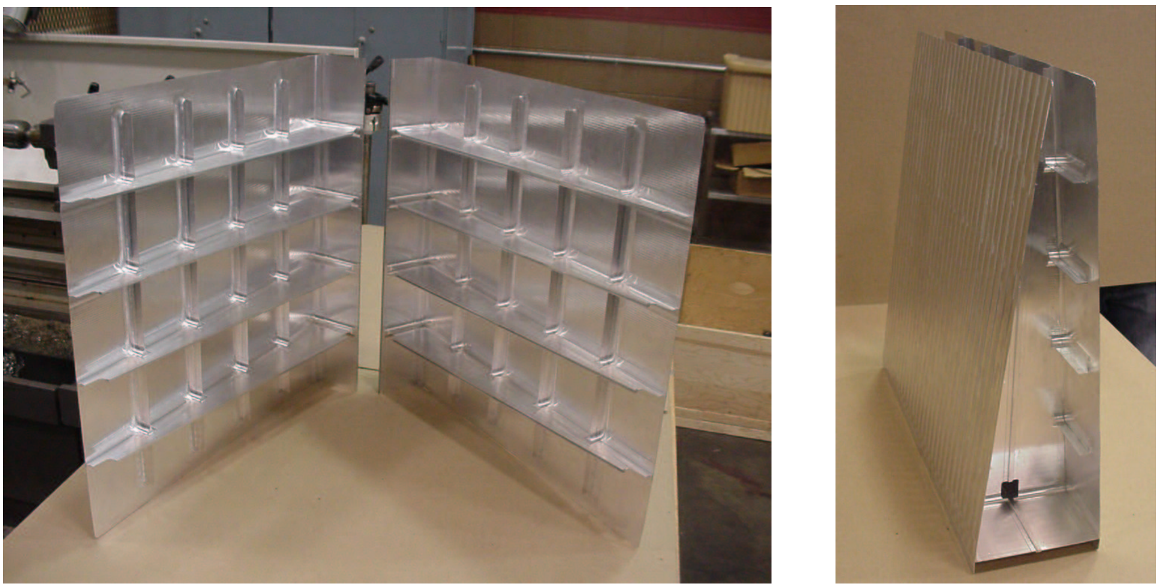

Figure 1: Test article for gridlock experiments. Some of the panels are buckled by residual stresses. Reproduced with permission from The Boeing Company.

Part distortion due to residual stresses present in aluminum mill products is a chronic problem in machining, resulting in high inspection, rework and scrap costs. While distortion has long been a problem in parts machined from forgings, plate stock has been considered a stable material for machining. However, thin unitized structural components manufactured by the means of HSM techniques also experience distortion, because the structure has less resistance to bending. Distortion problems are being observed in a variety of HSM components. A test article, typical in complexity and size of unitized structural components is shown in Fig. 1.

Residual stresses impact assembly as well as detail part fabrication. Advanced assembly technologies such as determinant assembly, which utilizes part-to-part indexing rather than expensive assembly fixtures, require parts manufactured to tight tolerances. Residual stress problems prevent full implementation of these new assembly technologies and achievement of the significant cost savings they offer. The complex component configurations resulting from structural unification, with wide variations in geometry over the plan area of the part, increase the chances for distortion. Thus, methods are required to design these components and develop the machining techniques that will ensure reliable component quality and affordability.

There are strong economic incentives for increasing material utilization factors, reducing machining times and increasing the success rate for machining unitized structural components, such as spars, keel beams, bulkheads[1]. A reliable virtual fabrication environment is essential for controlling the costs associated with fabrication of complex aircraft components and improving the quality of the design process.

Accomplishments

The main accomplishments of the project are summarized in the following:

1. The relationship between machining sequences and distortion was analyzed under the assumption of linearly elastic response. A theorem stating that, under the assumptions of linearly elasticity, distortion depends on the initial residual stress distribution and the final configuration only. A paper presenting the details of this work has been submitted for publication to the AIAA Journal. Authors: Nervi, Szabó and Young (see Publications).

2. The distribution of residual stresses in 7050-T7451 aluminum plates was determined by two different destructive experimental methods in which specimens were cut either by electrical discharge machining (EDM) or milling. Data received from Los Alamos National Laboratory through the courtesy of Dr. Michael Prime and data developed in the course of the present investigation were utilized. The residual stress distribution was estimated through the solution inverse problems. In both cases the model used for the determination of residual stress profiles included the assumption of plane strain conditions. The justification of this dimensional simplification was based on experimental measurements of the strains transverse to the cuts. Implied is the assumption that the residual stress profiles are independent of the the stresses in the transverse direction. The validity of this assumption was investigated and it was found that for proper interpretation of the data generalized plane strain models or fully three-dimensional models

[1]Economic estimates have been developed by Dr. David M. Bowden, Technical Fellow, The Boeing Company, St. Louis, MO 63166 Tel. 314-232-1859, david.m.bowden@boeing.com.

are required. Details are available in the doctoral dissertation of Sebastian Nervi and in a paper by Nervi S. and Szabó B. (2006) (see Publications).

3. Predictions based on mathematical models were compared with experimental observations. It was found that for moderately thin parts (wall thickness 5 mm or greater) predictions of distortion based on these models are consistent with experimental observations. The differences between predictions and experimental observations can be explained by irreducible uncertainties associated with the initial residual stress state determined by coupon tests. For specimens of small wall thickness (less than 5 mm) the effects of boundary layers introduced by milling tools become significant. X-ray diffraction measurements performed at Wright-Patterson AFB indicated that large residual stresses exist in a thin surface layer. The magnitude of stresses and their gradients depend on the milling tool, the spindle speed and other settings. A paper presenting the details of this work has been submitted for publication to the AIAA Journal. Authors: Nervi, Szabó and Young (see Publications).

4. The development of mathematical models that account for boundary layer effects was undertaken. The formulation is described in the doctoral dissertation of Sebastian Nervi.

5. Validation experiments have been performed. The mathematical model did not account for machining-induced residual stresses. Therefore thin surface layers were removed by chemical milling The resulting configurations were consistent with the predictions based on the mathematical model. Details are available in the doctoral dissertation of Sebastian Nervi.

6. An investigation of a dimensionally reduced model, called the generalized plane strain model, was undertaken in collaboration with Professor Ivo Babuska of The University of Texas at Austin. The results of this investigation have been published. See Babuška and Szabó 2006.

7. In the course of this project a document entitled "Guide for Verification and Validation in Computational Solid Mechanics" was published by the American Society of Mechanical Engineers[2] which was approved by the American National Standards Institute (ANSI), therefore it is considered to be an American National Standard. The objectives of this guideline are very closely related to the general objectives of this project.

   This publication represents an important milestone because it points to the need to control errors related to the definition of mathematical models and the errors related to their numerical solution. Given the importance and authority of this publication, it is unfortunate that the terminology reinforces, even aggravates, the existing widespread confusion surrounding the problem of quality assurance in numerical simulation. Another serious shortcoming of the document is that it does not provide adequate guidelines on how verification of the accuracy of computed data can be performed in professional settings.

[2] Guide for Verification and Validation in Computational Solid Mechanics. The American Society of Mechanical Engineers, New York, V&V 10-2006. ISBN #: 079183042X.

Specific application of quality assurance procedures in numerical simulation requires a systematic process, consisting of conceptualization, verification and validation. The Principal Investigator submitted a critique and proposed revisions to the ASME Committee PTC 60[3], responsible for this document, on March 12, 2007. In addition, a paper that elaborates on the proposed revisions and presents an example involving the application of conceptualization, verification and validation is in press. (Szabó and Actis 2008)

8. One of the important tools of conceptualization is virtual experimentation. Virtual experimentation is used for evaluating the influence of alternative modeling assumptions on the data of interest. This necessitates the use of hierarchic sequences of models. The procedure was illustrated in a paper (Szabo and Muntges 2005).

Publications

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Theses and Dissertations

Nervi S. A mathematical model for the estimation of the effects of residual stresses in aluminum plates. D.Sc. Dissertation, Department of Mechanical and Aerospace Engineering, Washington University, St. Louis, May 2005.

Persons supported

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Dr. Ricardo L. Actis, Affiliate Professor, Department of Mechanical, Aerospace and Structural Engineering, Washington University, St. Louis.

[3]Performance Test Code Committee 60. Verification and Validation in Computational Solid Mechanics.

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Daniel Muntges, Graduate Student, Department of Mechanical, Aerospace and Structural Engineering, Washington University, St. Louis - Currently employed by The Boeing Company in St. Louis.

Outlook

There is a growing interest in the establishment of procedures for verification and validation in computational solid mechanics, as evidenced by the publication of the ASME Publication Guide for Verification and Validation in Computational Solid Mechanics, V&V 10-2006 and the rapidly increasing number of papers being published and workshops conducted on the subject. Indeed, one cannot reasonably base engineering decisions on computed information without believing that the information is sufficiently reliable to support those decisions.

The conceptual framework of V&V is now well understood by a small circle of leading researchers, however transition of that framework into professional practice is facing several major obstacles. To remove those obstacles the US Air Force and other purchasers of computed information must insist on strict adherence to the application of verification and validation procedures by the suppliers of that information. Full implementation of such policy will be made possible only upon substantial revisions in current practices and supporting software products.

An important open question is the formulation of criteria for the rejection of models in validation experiments. Uncertainties are always present in physical systems, even under carefully controlled experimental conditions, therefore when predictions based on a mathematical model are compared with the outcome of physical experiments then those comparisons must be evaluated taking into account uncertainties in initial conditions, material properties and boundary conditions. In view of the fact that in general very few experimental data are available, the possibilities of rejecting valid models and not rejecting invalid models exist.

The approach described in [7] appears to be the most promising. This approach employs the methodology of Bayesian statistics. It involves selecting and fitting alternative models to the available prior information and then sequentially rejecting those which do not perform satisfactorily in the validation experiments. The rejection procedures are based on Bayesian updates, where the prior density is related to the current candidate model and the posterior density is obtained by conditioning on the validation experiments. The result of the analysis is quantification of the confidence in the computation, depending on the amount of available experimental data. An important aspect of this approach from the perspective of engineering decision-making is that the quantification of confidence in mathematical models can be improved as new data become available.

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[3] American Institute of Aeronautics and Astronautics (AIAA). Guide for the Verification and Validation of Computational Fluid Dynamics Simulations. AIAA-G-077-1998. Reston VA (1998).

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